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16. ABSTRACT

A general discussion of urban runoff pollution including the impact of urban runoff on water quality, and the control and handling of non-point source pollutants is presented. The importance of various planning and design considerations are stressed. Long range control planning, management strategies, runoff simulation and various computer models such as SWMM and STORM are discussed. The benefits of source and collection system controls are presented on a cost-effective basis, and a review is made of innovative physical/chemical treatment processes. The information is presented in the form of a literature review.

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Urban runoff and combined sewer overflow

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The impact of urban runoff on water quality is a problem of increasing significance in the field of water quality management.[1] With provisions for the control of municipal and industrial wastewater having been made by the U. S. Environmental Protection Agency (EPA), in accordance with the Federal Water Pollution Control Act of 1972 (PL 92-500), there is increasing concern over the control of nonpoint sources of pollution.

A report to Congress,[2] which reviewed the status and problems of an $8 billion project aimed at controlling flooding and combined sewer overflows (CSO) in Chicago, recommended that Congress define the extent of federal assistance available to urban areas for programs of this type. Serious questions were raised concerning the implementation and efficient coordination of projects shared between local, state, and federal agencies.

While PL 92-500 addressed the control of wastewater pollution through the requirement of a minimum of secondary treatment at municipal wastewater facilities, no clear national policy has ever been established requiring any technology-based effluent limitation for CSO.[3]

EPA analyzed five legislative alternatives for the control of CSO, recommending that funding of CSO pollution abatement projects be

continued under the existing provisions (Section 201) of PL 92-500.[4] Continuation of the present program was deemed the best alternative since it is a working program and could be more rapidly modified by administrative guidelines than legislative action.

The concept of best management practices (BMP) is currently the accepted approach for the abatement of nonpoint sources of pollution. Minton *et al.*[5] examined the relationship between BMP and receiving water quality standards, recommending the use of standards as a measure of the effectiveness of BMP programs. McPherson[6] noted that operation and maintenance costs of BMP can be very significant. Oberts[7] reviewed the water quality effects resulting from potential BMP, recommending with others,[8] that nonpoint sources of pollution be addressed before secondary treatment plants are upgraded any further.

Spooner *et al.*[9] reported on a framework water resources planning model that was developed and tested for Washington, D. C. A comparison was made of six management strategies for 1992, including secondary waste treatment, advanced waste treatment, stormwater treatment, water conservation, dry waste collection, and indirect estuary reuse. The water conservation strategy was shown to have the greatest cost-effectiveness.

According to Grigg,[10] a comprehensive framework coordinating federal, state, and local government agency programs is needed to effectively institute BMP for urban runoff control. Hiller *et al.*[11] discussed legislative and judicial techniques for controlling runoff.

The magnitude of the problem necessitates an expanded research effort to generate data necessary to address the most basic questions. EPA's urban runoff pollution control research and development program has sponsored over 150 projects in this area. Carlsson and Svensson[12] reported that 40% of geohydrological research in Sweden is being focused on urban runoff, particularly, on ways that runoff can be infiltrated back into ground water with minimal treatment.

For the past 4 years, annual symposiums on urban stormwater management have been held at the University of Kentucky. The symposiums have included the presentation of technical papers as well as indepth minicourses that have been identified as the most effective method of disseminating information on stormwater management techniques.[13]

In England, an international conference addressed the problem of urban storm drainage and resulted in the published proceedings of over 50 papers.[14] In the U. S., four technology transfer seminars sponsored by EPA were held on CSO abatement and control procedures,[15] and the proceedings of workshops on urban stormwater management and stormwater sedimentation and flood control have been published.[16, 17] Specific papers from the EPA technology transfer seminars are incorporated in this review. Wanielista[18] published a college text and solution manual on stormwater management. The text material could be completed in 44 classroom hours and deals with meteorology, hydrographs, routing, receiving water quality, and management practices for urban as well as non-urban runoff.

CHARACTERISTICS

Discharges of stormwater alone can seriously affect water quality, and Pirner and Harms[19] concluded that urban runoff was the major contributor of pollutants to receiving waters from a 70-km^2 (27-sq mile) watershed studied in South Dakota. For a 1 875-km^2 (724-sq mile) area sampled in Dallas,[20] a 12-hr storm event contributed 75% of the biochemical oxygen demand (BOD) pollutant loading and 99% of the total suspended solids (TSS). In the Milwaukee River, large dissolved oxygen (DO) sags were observed downstream from storm events.[21] The cause was identified as CSO, which had a scouring effect on the river's benthic deposits on discharge. In Houston, pathogenic concentrations in storm water varied with peak flow rates for both urban and rural areas.[22]

The concentration and loading of pollutants in storm water is important for proper evaluation of management strategies. Mueller and Anderson[23] discussed a mathematical model for assessing the characteristics and magnitude of CSO based on wastewater treatment plant monitoring records and mass and flow balance equations. Characklis *et al.*[24] summarized the findings of a 3-year study of watersheds near and in Houston, Tex., which established relationships between land use and stormwater quality and between rainfall intensity and pollutant loading. In a Norwegian study,[25] a correlation between the pollution concentration and percent impervious surface was identified. Combined sewers carried almost twice the pollutant mass of separate sewers. Tupper and Waller's[26] preliminary results revealed that the ratio of pervious to impervious surfaces is not correlated with the ratio of percent of runoff from storms.

Storm runoff sampling results from a catchment of Stevenage, New Town, England,[27] showed that the behavior of suspended solids (ss) and of heavy metals is very closely related, with at least 90% of the heavy metals being present in the particulate phase, or being rapidly adsorbed on ss at the time of sampling. Slimak and Harris [28] reported that stormwater discharges collected for artificial recharge of ground waters appear to present the most significant source of potentially toxic organic residuals contaminating Long Island aquifers.

In relation to PL 92-500, more emphasis should be placed on the problems, effects, and management practices associated with nonpoint pollution sources.[29] In response to this need, McPherson [30] prepared a report to assist planners and agencies in dealing with long-range planning of urban runoff control that would also be helpful to the 208 planner. Many issues that are commonly overlooked in the planning process were cited, and a compilation of papers dealing with urban runoff controls was presented. Rimer and Nissen [31] reported on the major findings of a 208 areawide wastewater management plan and identified and evaluated the effects of nonpoint source runoff as it is related to land use and water quality. Novotny and Goodrich-Mahoney [32] did a similar study for the Great Lakes area, and concluded, by using a calibrated and verified hydrologic transport model, that large amounts of nonpoint source pollutants are washed into surface waters. With the exception of developing urban areas, most of the nonpoint source urban pollution originated from impervious areas. According to Judd and Carlson,[33] the major contributors of pollutants to receiving waters are agricultural and urban runoff. Studies [34] have shown that both agricultural and urban runoff have high concentrations of phosphorous, which is deposited in stream sediments.

Fecal material from dogs is a significant urban runoff pollutant. Dog wastes and fertilizers contribute 23% and 22%, respectively, of the nitrogen contained in San Francisco's annual runoff.[35] A study in England [27] estimated that for a catchment area of 136 ha, serviced by separate sewers, 20 tons of wet dog feces is annually added to the pollutant load of the runoff.

Goettle [36] discussed the sources, characteristics, and concentrations of pollutants entering rain and storm water from the air, using two equations. Randall *et al.*[37] reported that washout of atmospheric contaminants occurred during the early stages of precipitation events. Horkeby and Malmquist [38] discussed the findings of an investigation on a catchment in Gotenburg, Sweden. Fallout of 17 heavy metals, polychlorinated biphenyls, hexachlorobenzene, and polynuclear aromatic hydrocarbons was studied. Pope *et al.*[39] discussed the results of an investigation of oil, lead, hydrocarbons, metals, and solids in runoff from roadways and the effect of these pollutants on the environment. Malmquist and Svensson [40] reported on a model being researched to predict concentrations of pollutants in storm water. Preliminary results indicated a relation between phosphorous levels and population and between lead and traffic levels. ss and chemical oxygen demand (COD) were related to population and traffic.

In Australia,[41] a study is being conducted to identify the types of land disturbances and their effects on the hydrological and sedimentation characteristics of their catchments. Lack of data has been an inhibitor to the successful application of numerical models for simulating rainfall-runoff-sediment processes. A study in Virginia [42] monitored six representative sources using automatic samplers and flow measuring devices in an attempt to define runoff characteristics on the basis of land use. Mattraw and Sherwood [43] monitored 106 runoff producing storms in a 19-ha residential area in Florida which was 61% lawns and 39% impervious surfaces. Storm water was routed in grassy swales and runoff was typically 5 to 10%

PLANNING AND DESIGN CONSIDERATIONS

McPherson [44] surveyed the technical issues of importance for long range urban runoff control planning to assist agencies participating in the development of comprehensive areawide plans and explored the mechanics of coordinating comprehensive plans. It was recommended that such plans allow for continual development to remain long range. Murphy [45] discussed the considerations that should be explored when developing a CSO master plan. The report outlined what should be included in a facility planning study and enumerated 15 major areas to be considered for construction and evaluation of a framework for a CSO system. Driscoll and Mancini [46] provided methods for estimating the benefits of controlling CSO, discussed equations for receiving stream analyses, and outlined what should be included in a 201 facilities plan for CSO.

Jalal [47] provided a methodology for screen-

ing urban development and runoff control alternatives using results of the STORM model to calculate a pollutant loading index. The index formed a basis for comparison of alternatives, and determinations of the optimum storage-treatment combination were effected. A cost-effective comparison of management strategies including separate storm and sanitary systems, conventional combined system, and advanced combined system with varying amounts of in-pipe and/or satellite storage and controlled flow routing, was made in Elizabeth, N. J.[48] Alternatives for pollution abatement from sewer overflows and stormwater discharges were evaluated using the SWMM and STORM models to characterize combined sewage and stormwater runoff in a 265-ha (655-acre) drainage district of the city.

Good data are essential for developing and evaluating a model, and Huber and Heaney [49] gave a list of requirements including amount of rainfall, runoff peak flow, and durations. Some possible sources of acceptable data were given. Alley [50] presented guidelines for the collection and use of urban stormwater data, including an overview on modeling and a comprehensive examination of network planning and design. Information concerning the instrumentation and coordination of a data collecting program was included. Van den Berg [51] described a data acquisition system based on a programable desk calculator as controller. The system allowed for continuous monitoring of precipitation, storm drain discharge, subsurface drainage and groundwater level. Verworn [52] discussed the apparatus and results from an integrated electronic data collecting system. The system measured and recorded both rainfall and discharges into the sewers. By the use of 4 rain gauges and 10 water level gauges in an integrated system the data are transmitted to a central recording office. The only conclusion that has been drawn is that the lag time between rainfall and runoff is 3 minutes at most, which is less than documented in many references.

Changon and Huff [53] reported progress through the first 2 years of the Chicago Hydrometeorological Area Project (CHAP) towards its Phase II goals of developing a prediction and monitoring system for specifying rainfall quantity over the area. A methodology for using precipitation data for hydrologic models for the design of hydrologic systems is also being developed. Monitoring facilities include a dense drainage network of over 320 recording rain gauges and a 10-cm weather radar with state-of-the-art signal processing and an attached computer that allows for rapid digitization of rainfall data. Melanen [54] described the objectives and results of a 3-year Finnish urban stormwater project now in its second year. The project's objectives include identification and quantification of the sources and transport of pollutants and analysis of the factors affecting stormwater quantity and quality.

Toyokuni and Masahiro [55] presented techniques for catchment modeling and runoff simulation for urban areas. Models used were based on the kinematic wave method relating to runoff. Sherman [56] discussed a kinematic model for overland flow and showed all equations necessary for evaluating two cases, with and without ground infiltration. Based on data from 41 urban watersheds, empirical equations were developed by Espey *et al.*[57] to aid in synthesis of 10-minute unit hydrographs. Scaled nomographs of five descriptive parameters were given along with a sample 10-minute unit hydrograph. Hossain *et al.*[58] studied linear and non-linear system models to determine the response of watersheds during different stages of urbanization. It was concluded that an urban watershed is non-linear and that the accuracy of the instantaneous unit hydrographs (IUH) depends on the time interval and digital filtering used in getting readings for the IUH. Jewell *et al.*[59] used the SWMM model to illustrate a new approach for calibrating quality and quantity independently. Verification revealed a need for improved methods for predicting pollutant accumulation rates.

Mays and Tung [60] presented a sewer network flow-routing model based on a state variable approach to systems analysis and synthesis. This lumped mathematical model is capable of describing temporally and spatially varied flow through sewer networks. Price and Kidd [61] described a design and simulation method for storm sewers, similar to the TRRL method, but using a surface runoff model that treats paved and roof areas separately. The pipe flow routing method used makes allowance for upstream surcharging of a pipe. Arnell and Lyngfelt [62] presented information on a variation of the Preul and Papadakis urban runoff model. The model divides the runoff into five categories: (1) infiltration, (2) surface depression, (3) overland flow, (4) gutter flow, and (5) sewer routing. The model takes in data from hyetographs and produces runoff hydrographs. This modified model was

verified to be most accurate for single storm events in small catchments with high percentages of impervious surfaces.

Packman [63] described a planning model called FLOUT, which simulates flooding in partly urbanized catchments. By using recorded data collected over a 16-year period, the FLOUT model was compared to the actual flow curve and a simple unit hydrograph. The results show the predicted hydrograph superior to the simple hydrograph and very similar to the actual flow; however, it tends to over-predict the beginning and underpredict the recession of the hydrograph. A synoptic rainfall data analysis program (SYNOP) was developed for use as a tool to summarize important variables of hourly rainfall recorded to determine seasonal trends.[64] Hajas *et al.*[65] described an assessment made of a 17 353-km^2 (6 700-sq mile) area in southwestern Pennsylvania, to predict the urban runoff flows and loads. The STORM model was selected and field data were obtained using automatic samplers and flow meters. Results were used to adjust computer input data to obtain more accurate model simulation. Wu and Ahlert [66] reviewed state-of-the-art methods for predicting storm runoff pollutant loads. Predictive approaches required efficient samplings and technically sounder methods of data analysis. Application of a particular approach was found to depend on the purposes of prediction and availability of resources.

Tucker and Mortimer [67] discussed the equations and results of a solids model based on first flush and subsequent solids behavior, a flow model using both Vessman hydrographs and Watkins time area method, and a solids pollution generation model. Price and Mance [68] described a mathematical model to predict the amounts of ss in runoff from an urban water catchment. This model was tested against observed events and shown to be more "realistic" than the conventional SWMM and STORM models.

Boggs *et al.*[69] discussed the use of the STORM model along with mathematical equations for the prediction of flow and loads of storm water in an areawide 208 program. This information was then used in a design storm and receiving water models that included costs and treatment processes. Quick and Pipes [70] gave an outline description of a hydrologic model used on the University of British Columbia watershed that calculates snowmelt and rain runoff from meteorological data for mountainous watersheds. A revised temperature index for calculation of snowmelt and a parameter for describing enhanced watershed response from high intensity rainfall were presented.

Torno [71] reported on presentations of the U. S. and Canadian SWMM Users Group meeting of November 1977. A new version of SWMM was presented, along with various other pertinent papers. Perks [72] and others [73] discussed a Canadian SWMM user's manual that expanded the capabilities of the original SWMM by integrating snowmelt quantity and quality models with it. A method of interfacing the STORM and SWMM models for application in Canada was discussed. A report by the Ministry of the Environment [74] described the second Canadian SWMM workshop that provided some background into the technology of urban stormwater modeling. Instructions were presented for setting up and conducting simulations for specific problem areas using the Canadian SWMM, and simulation results were discussed. Diniz [75] discussed modifications that were made to the EPA SWMM so the model could be used for an urban community using innovative drainage methods in a naturally drained area. The changes involved modification in the computation of infiltration and three subroutines which allowed for calculating normalized area discharge curves for natural channel sections, modeling of base flow conditions, and porous pavement. The transport part of SWMM was altered to contain a subroutine that computed discharge curves for flow routing of drainage systems. To improve the model estimates of total pollutant mass flow, direct user input data were necessary since a new methodology was "beyond the scope of the current project" presented. The predicted and actual results from this modified model were well correlated.

Price and Howard [76] evaluated two model storm profiles used in the design of pipe diameters and sewer systems in the United Kingdom. The RN 35 (Road Note 35) and the FSR (Nere Flood Studies Report) were compared; RN 35 used return period and location as the only variables, while FSR also used duration and peakedness. The FSR proved to give better predictions. Svensson [77] described a study of a catchment in Gothenburg, Sweden, which evaluated the SWMM model. Results showed the actual and simulated hydrographs were very close in one instance and not close in two others.

McPherson [78] examined current analysis procedures for storm drainage system designs and

concluded that the analysis of actual rainfall histories is of greater reliability for use by local officials than the use of a synthetic storm, especially where detention storage may be part of the system. Marsalek [79] described the use of synthesized and historical storms for calculating the peak flow and for urban drainage design. Results were compared with those of two actual events with the same return periods. Pennino and Perkins [80] discussed the hydraulic design of a diversion-retention facility in Richmond, Va., which was evaluated and refined using a 1:18 scale model.

SOURCE CONTROLS

Day and Crafton [81] presented various techniques for decreasing flood potential and runoff quantity. Basic site and community design guidelines for managing urban storm water were discussed within a conceptual framework that stressed the importance of land use in maintaining water quality. Pitt [16, 82] reported on the sources, types, concentrations, and costs of removal of pollutants from streets using various street cleaning practices. The location of the pollutants in the streets was discussed as well as the equipment used and effectiveness (pollutant removal). Malmquist [83] reported that street sweeping removed 57% of the ss and up to 65% of the heavy metals found on the street.

McBride *et al.*[84] described a rational method for determining the economic impacts of snow and ice control runoff on the surrounding environment and in controlling the amount of saline runoff from highways and stockpiles. An economic model, developed and verified on a small scale, was presented in a user's manual.[85] Krukar and Cook [86] reported on field testing and laboratory optimization of several hydrophobic coatings to reduce the adhesion of ice and snow to pavements; thereby reducing the use of salts. Some factors considered were pavement types, wear, environment, and toxicity . Preliminary results showed combinations of modified traffic paint and room temperature-curing silicon rubber to be the most effective formulas. Substances were optimized towards specified objectives, including cost effectiveness, minimum environmental pollution, and use of standard materials and equipment. Numerous formulations were laboratory and field tested and the substances were ranked on change in skid resistance, water beading, and snow/ice removal.[87]

North Carolina created a commission and a 26-member inspection force to implement its sedimentation pollution control act of 1973.[88] State construction sites received top priority consideration, and a self-funding program was initiated to educate construction contractors about the act.

Barfield *et al.*[89] discussed the Universal Soil Loss Equation and presented a new model for rational design of sediment detention reservoirs. Methods of stabilizing soil and preventing sediment from entering sewers and waterways were discussed. The amount of sediment and pollutants normally transported from urban areas to receiving waters can be greatly reduced by good land use planning resulting in storm drainage systems that use natural drainage and one-site stormwater detention storage.

According to Field,[90] flood, erosion, and pollution control technologies must be integrated so that retention and drainage facilities are simultaneously designed for pollution control. Additionally, land management and nonstructural techniques must be integrated and maximized to reduce the expenses of extracting pollutants at potentially more costly downstream plants.

Guy [91] emphasized good planning combined with surface stabilization and detention storage as the most practical means of sediment management and listed principles useful in accomplishing good planning and on-site storage. Tsuchiya [92] reported that, in Japan, detention ponds are required for any large-scale land development to prevent flooding. Methods for calculating peak flow and discharge, were explained.

Successful low-cost, dual-purpose variations of detention are ponding on parking lots, plazas, recreation and park area, and on rooftops.[53]

Thelen and Howe [93] discussed the composition of porous pavement, its properties, maintenance requirements, and the advantage of its use. A step-by-step method of evalauating the applicability of porous pavement for a site and for performing a site analysis were given.

Proctor and Redfern [94] assessed both on-site and downstream stormwater detention facilities in Canada and reported that rooftop storage is practical in most commercial and industrial areas. Detention facilities were indicated as being effective in reducing peak stormwater flow, while lowering overall drainage costs. Theil and Candaras [95] reported on the Hydrobrake, a device that can be used in combination with detention tanks for limiting the volume of runoff that enters the sewer system.

Studies in flood hazard areas showed the device to be effective.

Wanielista *et al.*[96] reported on research being conducted on the potential of aerobic and anaerobic shallow-water ditches along highways for hydrocarbon degration and deposition of heavy metals and petroleum products from automobiles. High metal concentrations in the soil, plants, and animal life near the roadway's edge decreased with distance from roadway. Wanielista and Yousef[97] discussed the possibilities of using retention basins as filtering percolation basins for storm waters' first flush. Laboratory and field data and equations used for determining dimensions and feasibility for a basin were given. Cederwall and Holstrad[98] discussed Swedish research on hydrological and geohydrological conditions relating to the use of stormwater percolation basins for recharge of groundwater supplies. The basins ranged from gravel filled trenches between houses to large, 0.81-ha (2-acre) basins under parking lots. Two full-scale projects have been set up. The basins are expected to recharge the aquifers as well as cut down on costs by reducing the amount of piping and decreasing volume of storm water routed to the treatment plant.

COLLECTION SYSTEM CONTROL

Giordano[99] reported observations of the effects of sewer separation on wastewater quantity and quality in an aluminum storm sewer system in LaSalle, Ill. The suitability of aluminum as construction material for the system is being technically evaluated over a 10-year post-construction period. Svensson and Malmquist[100] studied the quality and quantity of sewage flow for a separate sewer system in a suburban area in Sweden and reported that sanitary sewers take up to 30% of the total runoff volume. Sullivan *et al.*[101] discussed infiltration/inflow (I/I) as it relates to sewer system evaluation, rehabilitation, and design. Procedures for sewer system analysis and evaluation studies were provided, as well as a discussion on maintenance techniques, infiltration limits, and methods of testing for infiltration in new construction.

According to Good,[102] the benefit of using computers in sewer investigations, including flow monitoring, data analyses, sewer modeling, and economic analyses, is dependent on the type of system investigated and the accuracy of the information desired. Bettess *et al.*[103] gave an interim report on research on a simulation unrestrictive surcharging model, including the equations involved in partially filled and surcharged pipes. The final model will handle any number of surcharged pipes in any configuration. Trotta *et al.*[104] evaluated several on-line automatic strategies that rerouted storm water within a sub-basin area to minimize receiving water impacts. Weather forecasting proved to be the most important single factor in controlling overflows and was critical to the accuracy of the system. Response time and efficiency were optimized by computer control.

Stilley[105] presented a simulated field study for I/I analysis of a municipal sewer system, outlining the major considerations necessary for such a study. Goulart and Kovacs[106] summarized the results of an I/I analysis undertaken at Warren, R. I. A sewer system evaluation survey and economic analysis showed that reduction of inflow by 83% and removal of 80% of infiltration would be the most cost-effective alternative for upgrading wastewater treatment facilities. Sullivan *et al.*[107] surveyed local authorities to determine the extent and effect of tree roots in sewers. Backwater flow intrusion control was analyzed and guidelines for economic analysis of I/I control were outlined.

In Scotland,[108] a committee investigating the control and discharge of pollutants from storm overflows into receiving waters, studied the use of storage and setting tanks to detain CSO for treatment. The benefits of separate versus combined sewer systems were also studied. Systems were studied in which runoff from an area of concentrated pollutants (for example, a chemical loading dock area) would be diverted into the sanitary sewer system for treatment, while areas of low pollutant concentration would receive minimal treatment.

Polymers can be used to reduce turbulent flow and liquid friction in sewers, thereby increasing velocity. Polymer injection increased pumping station capacity 20% beyond design capacity in Bergen County, N. J.[109] Polymer injection was found to be a valuable alternative to the construction of parallel sewers in situations requiring expanded sewer flow capacity on rare, but predictable occasions. Peroxide, added to sewer lines in Corpus Christi, Tex., reduced odors and prevented further corrosion of concrete pipe.[110] Hydogen sulfide in sewer lines was completely oxidized by the peroxide into harmless byproducts. Test programs showed that hydrogen peroxide could be used economically

and effectively by replacing prechlorination at lift stations.

Kuntze [111] reported on an examintaion of the entire drainage system in Hamburg, Germany. A flow control system was developed that necessitated the expansion of the collecting sewer capacity and treatment plant capacity.

Beetschen and Henry [112] described and evaluated the installation of trenchless sewers using the Badger Minor method of plowing in solvent welded polyvinyl chloride pipe on a grade established by using a laser-controlled unit. The trenchless method was reported safer than conventional methods and showed significantly less potential for infiltration. The trenchless method represented an improvement over conventional installation methods in both sediment control and noise reduction.

Sonnen [113] described alternative methods for alleviating "first flush" pollution during high-flow, wet-weather periods and determined the feasibility of mathematically simulating the improvements afforded by these methods. Procedures for the modeling of deposition, scour, and transport processes and estimating the costs of the simulated facilities have been reported.[48, 114]

STORAGE

Storage of urban storm water with subsequent treatment, is an effective tool for reducing pollution from CSOs and is being incorporated into the stormwater management plans of many urban areas. The Chicago Tunnel and Reservoir Plan represents an application of the storage concept on a monumental scale. Phase I of the project, which is nearly half completed, consists of underground tunnels, linked to the surface drainage system at strategic intervals. The tunnels are designed to intercept and store combined sewer overflows, allow for instream aeration, and convey the storm water to detention reservoirs.[115]

Heaney *et al.*[116] discussed a generalized method for evaluating the optimal mix of storage and treatment for various levels of BOD control and estimated that the initial capital investments necessary for controlling urban runoff pollution nationally will be significantly lower than previously reported.

TREATMENT

Kerri *et al.*[117] examined the workings, applications, and design criteria of the Teacup Solids Separator. Pilot tests proved the Teacup to be more efficient than expected with up to 100% removal of settleable solids and floatables, 90% removal of ss and 40% removal of BOD. Field and Traver [118] discussed the development of three swirl devices (regulator/concentrator, primary separator, and degritter) being researched and used in the U. S. Information and data were given on five different cities that used swirl devices. Pilot studies and technical data on a swirl primary separator in Toronto were reported by Sullivan.[119] Results showed the swirl to be as effective as a settling tank, while operating at increased flow rates of two to three times that of conventional units and shorter time periods compared with those of settling tanks. Murphy *et al.*[120] evaluated a single unit process for the removal of ss, phosphorus, and nitrogen from CSOs. A bench-scale study demonstrated the feasibility of the dual use of a high-rate, physical-chemical process during wet- and dry-weather, respectively. Treatment unit costs were developed in a demonstration scale study.

Hickok *et al.*[121] demonstrated the effectiveness of a non-structural method to improve the quality of urban stormwater runoff using natural wetlands. Non-structural methods used physical, biological, and chemical mechanisms to remove nutrients.

Huibregtse [122] assessed the impacts that would result from fullscale treatment of CSO. It was estimated that an average yearly sludge volume of 156×10^6 m^3 (41.5×10^9 gal) could be expected nationwide from such treatment. Characteristics and volumes of sludge were found to vary widely, depending on the type of treatment process used. Osantowski *et al.*[123] reported that the dewatering of CSO sludges appears feasible when the sludges are first degritted, when required, and thickened prior to centrifugation. CSO and dry-weather sludges were both dewatered to cakes and the dewatering characteristics of wet/dry-weather sludge mixtures were similar to those for CSO alone.

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